Lattice flavor physics at BNL

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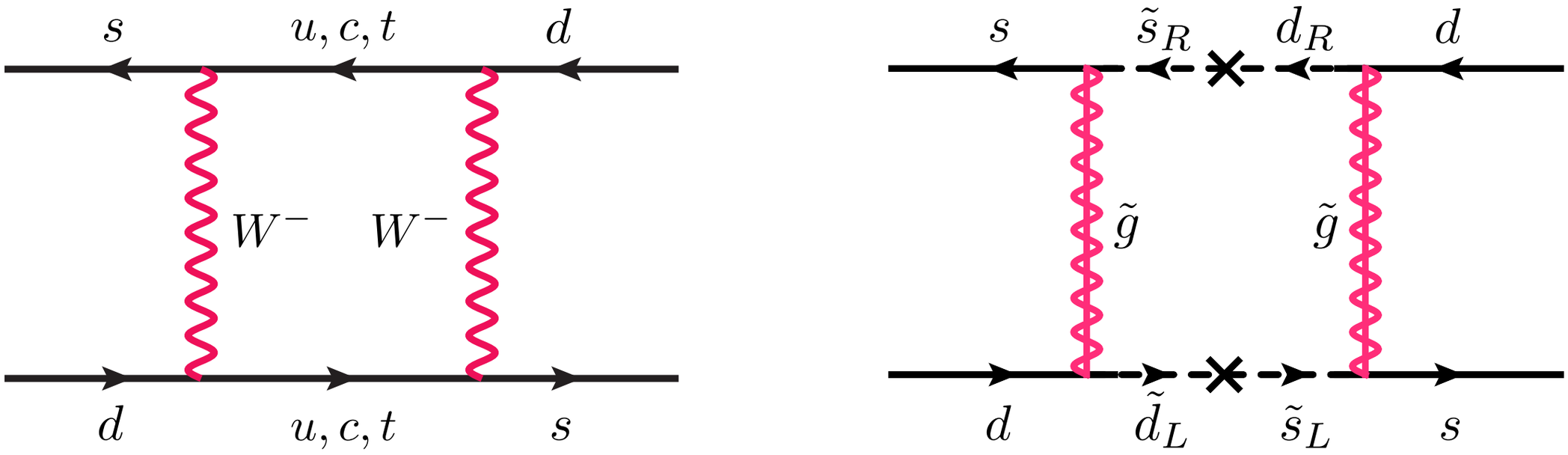
DOE Laboratories Theory Program Review
July 26, 2011

Why study flavor physics?

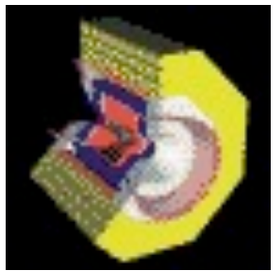
- Flavor sector sensitive to physics at very high scales
  - New particles typically appear in loop-level processes such as neutral kaon mixing:



- $\Rightarrow$ We may see evidence for new physics in the flavor sector before we produce non-Standard Model particles directly at the LHC!

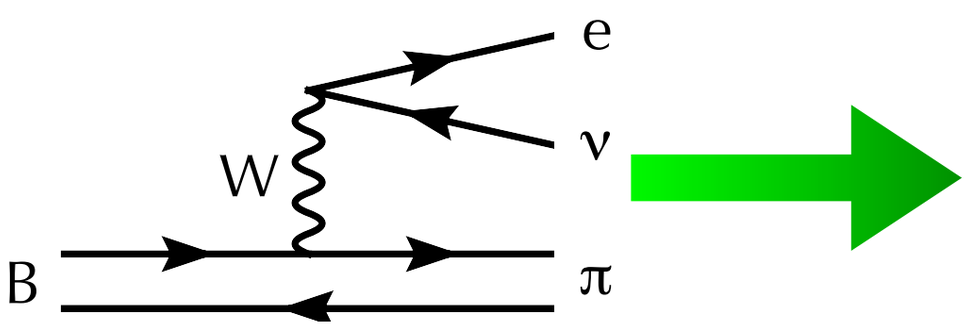
Lattice QCD and precision flavor physics

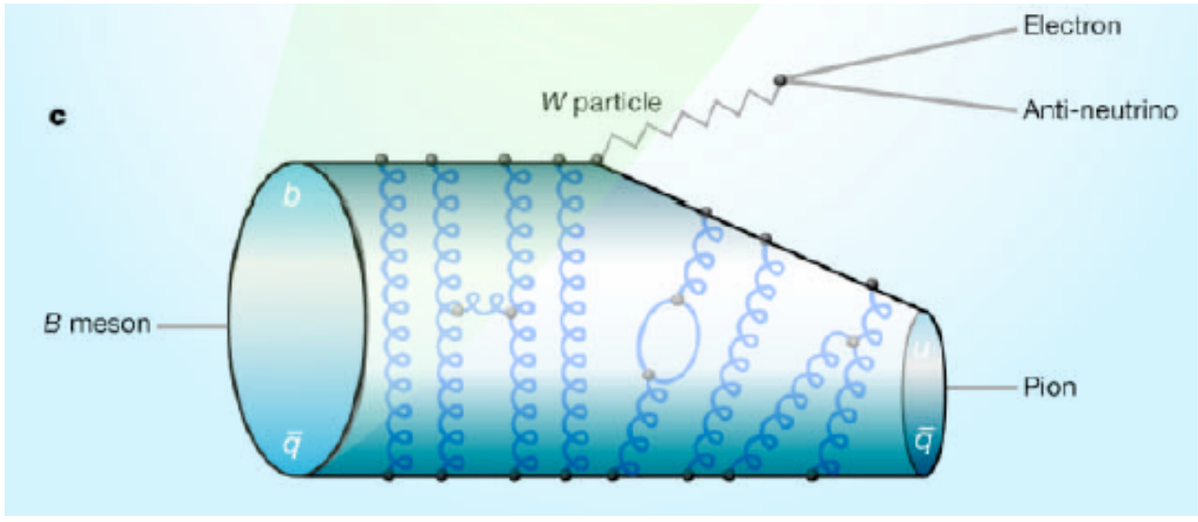
- Experiments pouring out data to pin down the CKM matrix elements, but **precise lattice QCD calculations of hadronic weak matrix elements are needed to interpret many of their results**



  - Schematically, EXPT. = PT × CKM × LATTICE

- To accurately describe weak interactions involving quarks, must include effects of confining quarks into hadrons:





- Absorb nonperturbative QCD effects into quantities such as decay constants, form factors, and bag-parameters which we must compute in lattice QCD

Lattice QCD constraints on the CKM matrix

$$\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \pi \to \ell\nu & K \to \ell\nu & B \to \ell\nu \\ & K \to \pi\ell\nu & B \to \pi\ell\nu \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ D \to \ell\nu & D_s \to \ell\nu & B \to D\ell\nu \\ D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ \langle B_d|\bar{B}_d\rangle & \langle B_s|\bar{B}_s\rangle & \end{pmatrix}$$

Lattice QCD constraints on the CKM matrix

- "Gold-plated" lattice processes allow the determination of most CKM matrix elements:
  - 1 hadron in initial state; 0 or 1 hadron in final state
  - Stable (or narrow and far from decay threshold)

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- Colleagues in RBC Collaboration are working on those circled in PURPLE
- As part of the MILC Collaboration Van de Water is helping with those circled in ORANGE

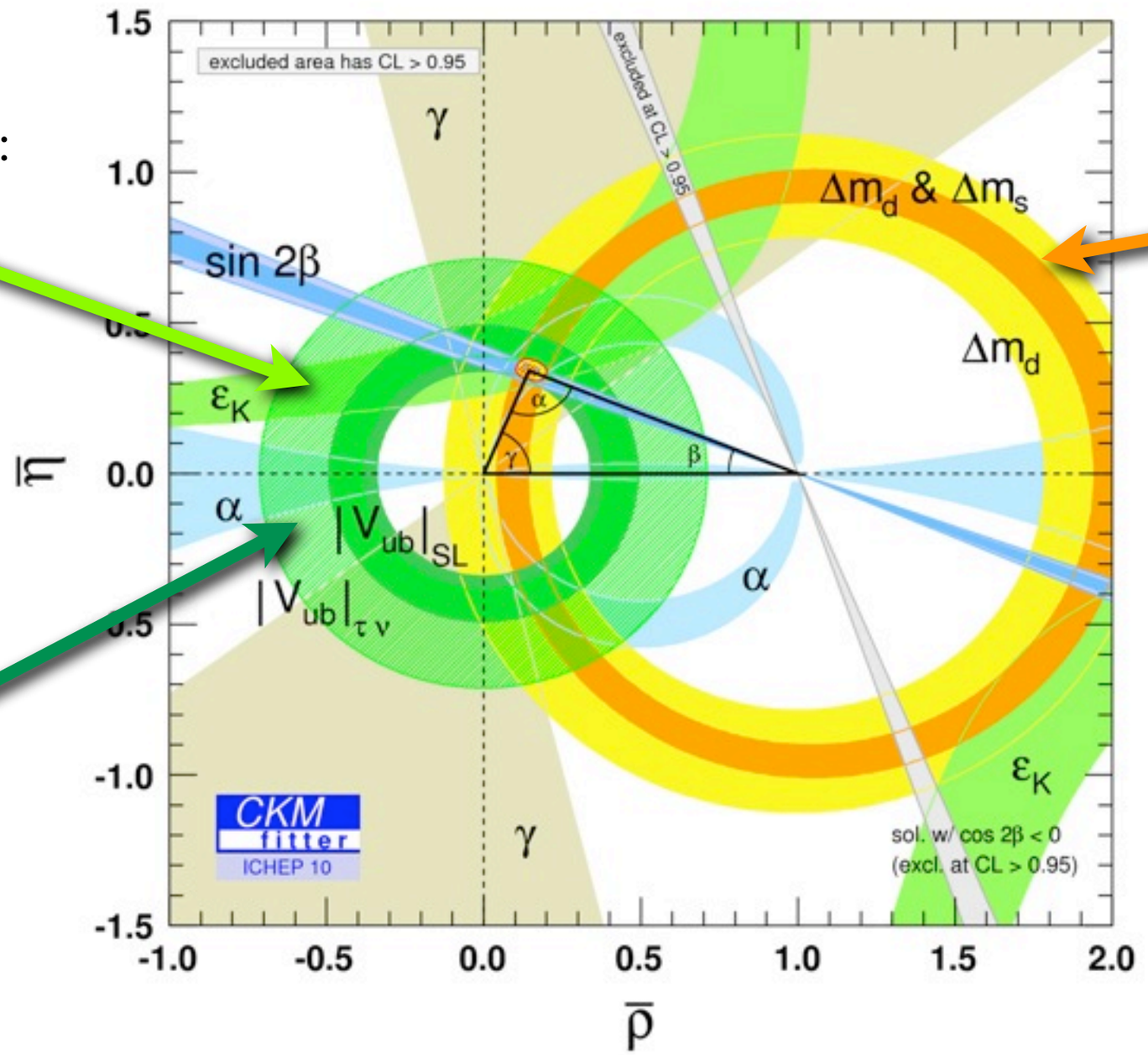
Lattice QCD inputs to the unitarity triangle

- Many constraints on the unitarity triangle require lattice QCD calculations of hadronic weak matrix elements
- BNL high-energy theory group is currently computing **several key inputs**:

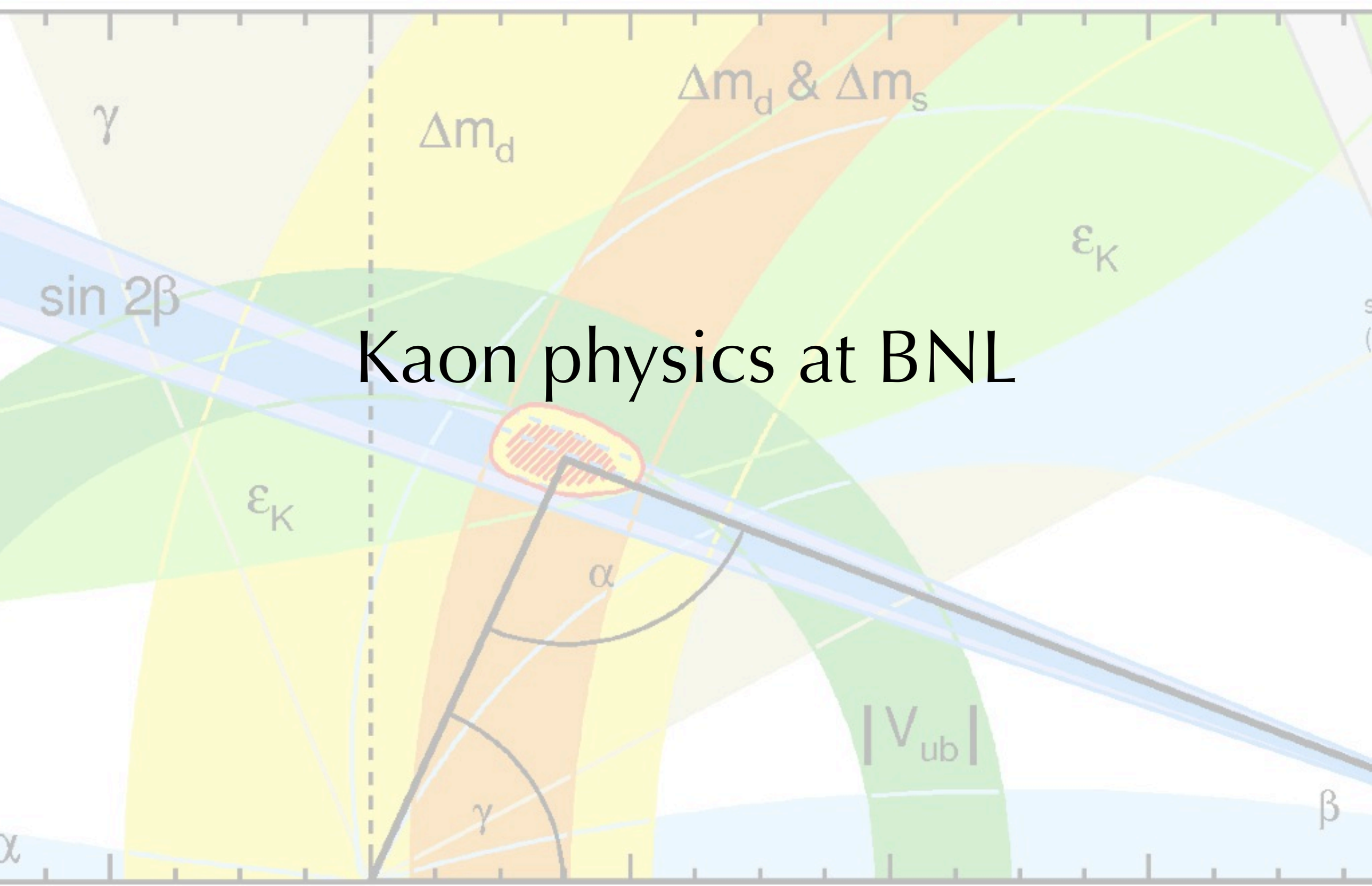
neutral Kaon mixing:
B_K

leptonic
$B \to \tau\nu$ decay:
$f_B \to |V_{ub}|$

B-meson decays
and mixing:
f_B & B_B



Kaon physics at BNL

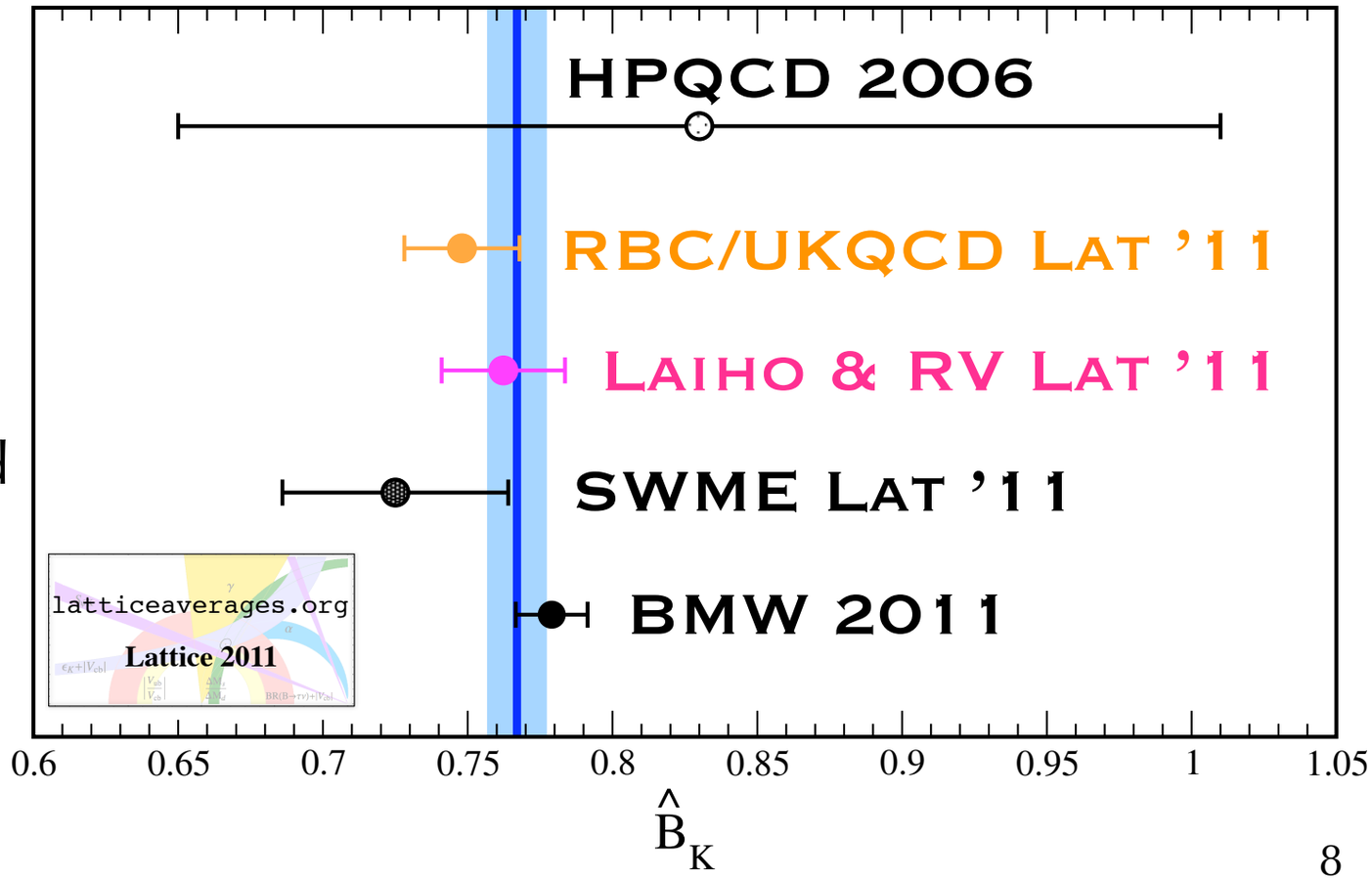


Project menu

- Two collaborations with members in the BNL HET group are computing kaon physics quantities with different lattice formulations
  - Izubuchi and Soni with the RBC/UKQCD Collaboration
  - Van de Water with J. Laiho at Glasgow
- **Independent results provide valuable cross-checks on phenomenologically-important quantities** such as:
  - **u,d,s-quark masses**: parametric inputs to Standard Model calculations and new physics predictions
  - **f_K/f_π**: allows precise determination of the ratio $|V_{ud}|/|V_{us}|$ [Marciano]
  - **$K\to\pi\ell\nu$ form factor**: needed to obtain $|V_{us}|$ (RBC/UKQCD only)
  - **B_K**: needed to interpret experimental measurement of indirect CP-violation in the neutral kaon system (ε_K) as a constraint on the apex of the CKM unitarity triangle
  - **$K\to\pi\pi$ decay**: needed to interpret experimental measurement of direct CP-violation in the kaon system ($\varepsilon'_K/\varepsilon_K$) as a constraint on the CKM unitarity triangle

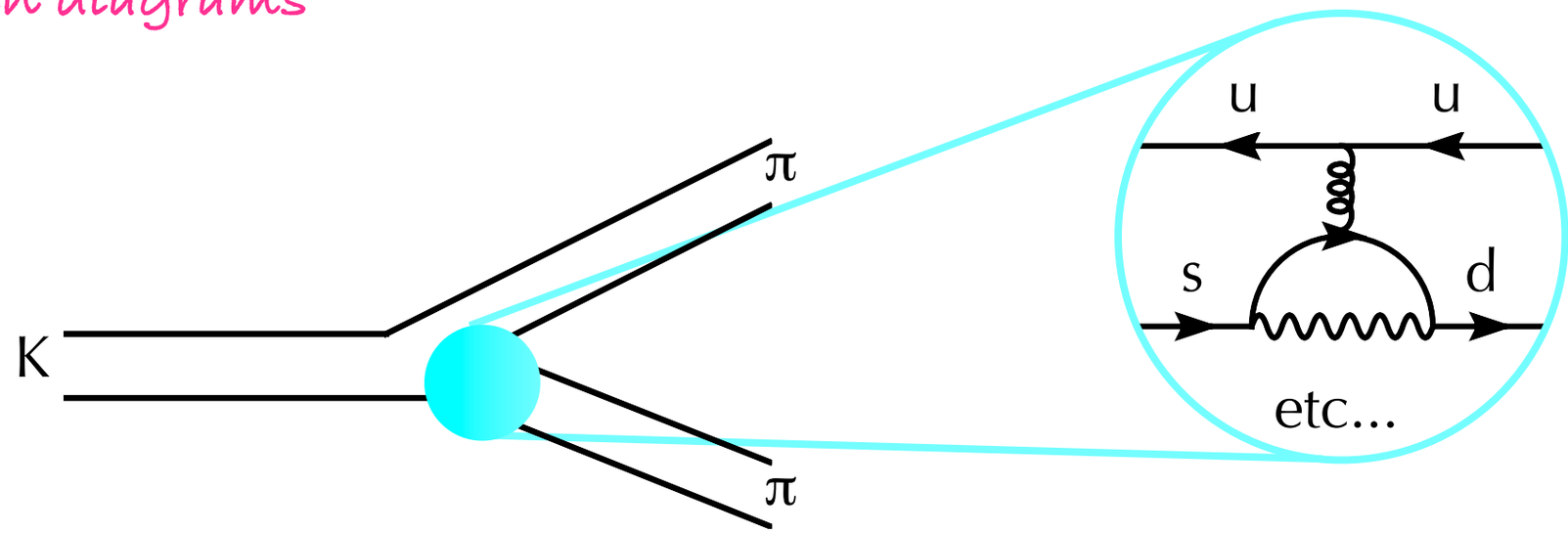
Highlight: neutral kaon mixing parameter B_K

- Until recently, the uncertainty in the ε_K band was primarily due to the ~20% error in lattice QCD calculations of the hadronic matrix element B_K
- 2007: RBC/UKQCD used domain-wall fermions to dramatically reduce error to ~6%
  - Improved precision largely due to approximate chiral symmetry of domain-wall fermions, which leads to continuum-like chiral extrapolations, straightforward nonperturbative renormalization, and small scaling violations
- 2009: Aubin, Laiho, & RV independently confirmed the RBC/UKQCD result using a different lattice formulation
- Since 2007: RBC/UKQCD developed a significantly better renormalization scheme; at Lattice 2011 they presented an updated result with a ~3% error
  - RV & Laiho also presented an updated B_K with similar errors



K→ππ decay

- Both **RBC/UKQCD** and **Laiho & RV** are independently calculating direct CP-violation in K→ππ decay
- $\varepsilon'_K/\varepsilon_K$ places a constraint on the CKM unitarity triangle (a horizontal band) that must intersect the solution established from ε_K + B-physics
  - Sensitive to new physics because it receives contributions from 1-loop electroweak penguin diagrams



  - ⇒ Compelling test of the Standard Model CKM framework and probe of new physics

- **Flagship project of RBC/UKQCD**
  - Chiral symmetry of domain-wall fermions important to control systematics associated with operator renormalization and subtraction of power divergences

RBC/UKQCD progress on K→ππ decay

- **Before 2008:** several attempts to compute $\varepsilon'_K/\varepsilon_K$ using chiral perturbation theory to relate simpler unphysical matrix elements to desired K→ππ amplitude [Bernard, Draper, Soni, Politzer, & Wise (LO); Laiho & Soni (NLO)]

- **2008:** demonstrated poor convergence of chiral perturbation theory at kaon mass [PoS(LATTICE 2008)272], so switched to direct Lellouch-Lüscher approach

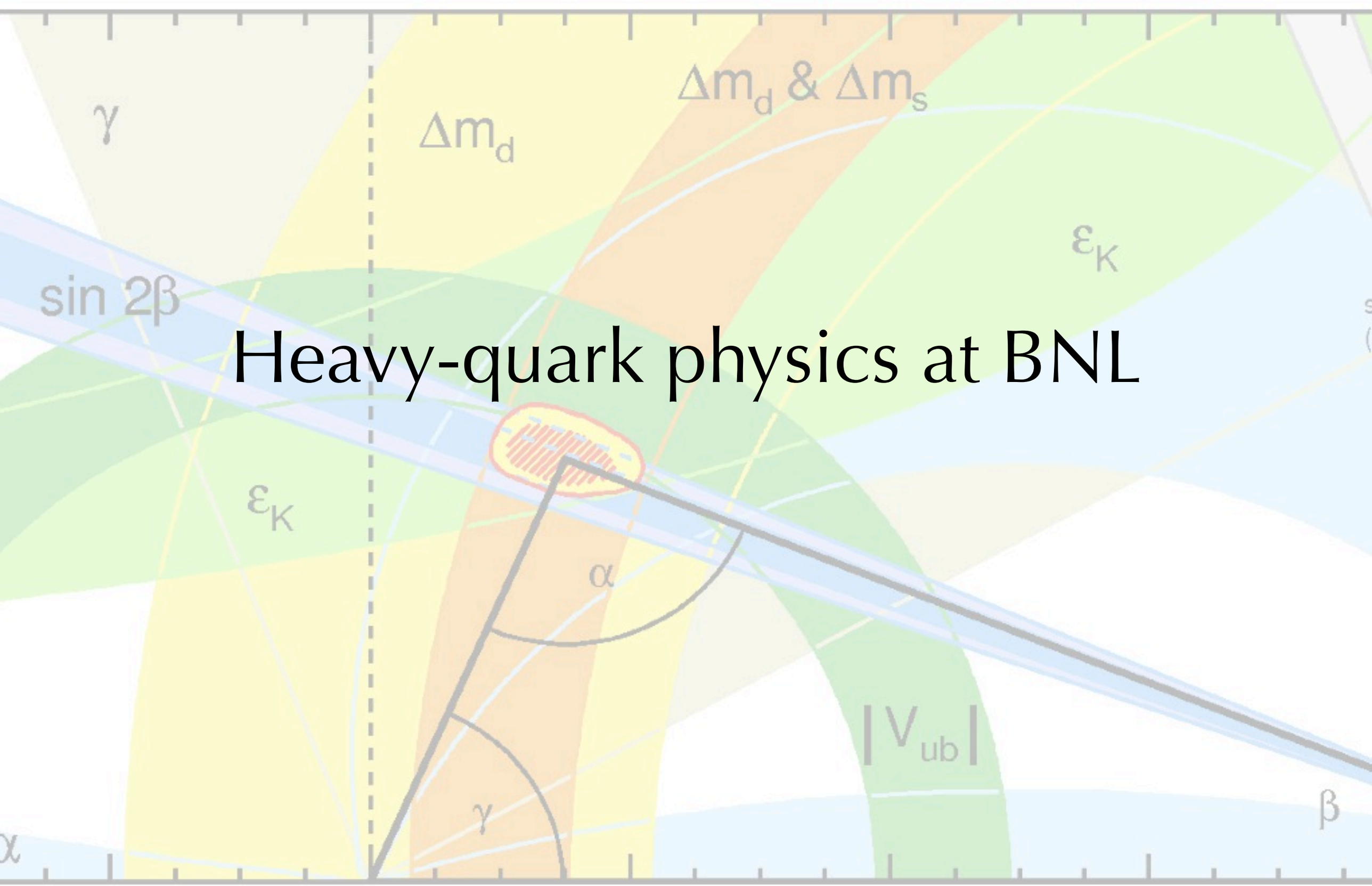
- **2010:** generated a dedicated ~$(6\ \mathrm{fm})^3$ coarse ensemble and computed $\Delta I = 3/2$ matrix elements with nearly physical pion/kaon masses [PoS(LATTICE2010)313]; update at Lattice 2011 presented $\mathrm{Re}(A_2)$ & $\mathrm{Im}(A_2)$ with ~15% errors [Goode, Lattice 2011]

- **2011:** studied $\Delta I = 1/2$ matrix elements with heavy pion at unphysical kinematics; demonstrated ability to perform power-divergent subtractions and tackle computationally-expensive disconnected diagrams [arXiv:1106.2714]; update at Lattice 2011 presented preliminary results for $\mathrm{Re}(A_0)$ & $\mathrm{Im}(A_0)$ with 330 MeV pions [Liu, Lattice 2011]

- Developed improved nonperturbative renormalization scheme for $\Delta S = 1$ operators [Lehner (RBRC) and Sturm, Lattice 2011]

- **2012+: QCDCQ installation will allow computation with larger volumes and lighter pions, enabling first realistic lattice QCD calculation of $\varepsilon'_K/\varepsilon_K$**

Heavy-quark physics at BNL



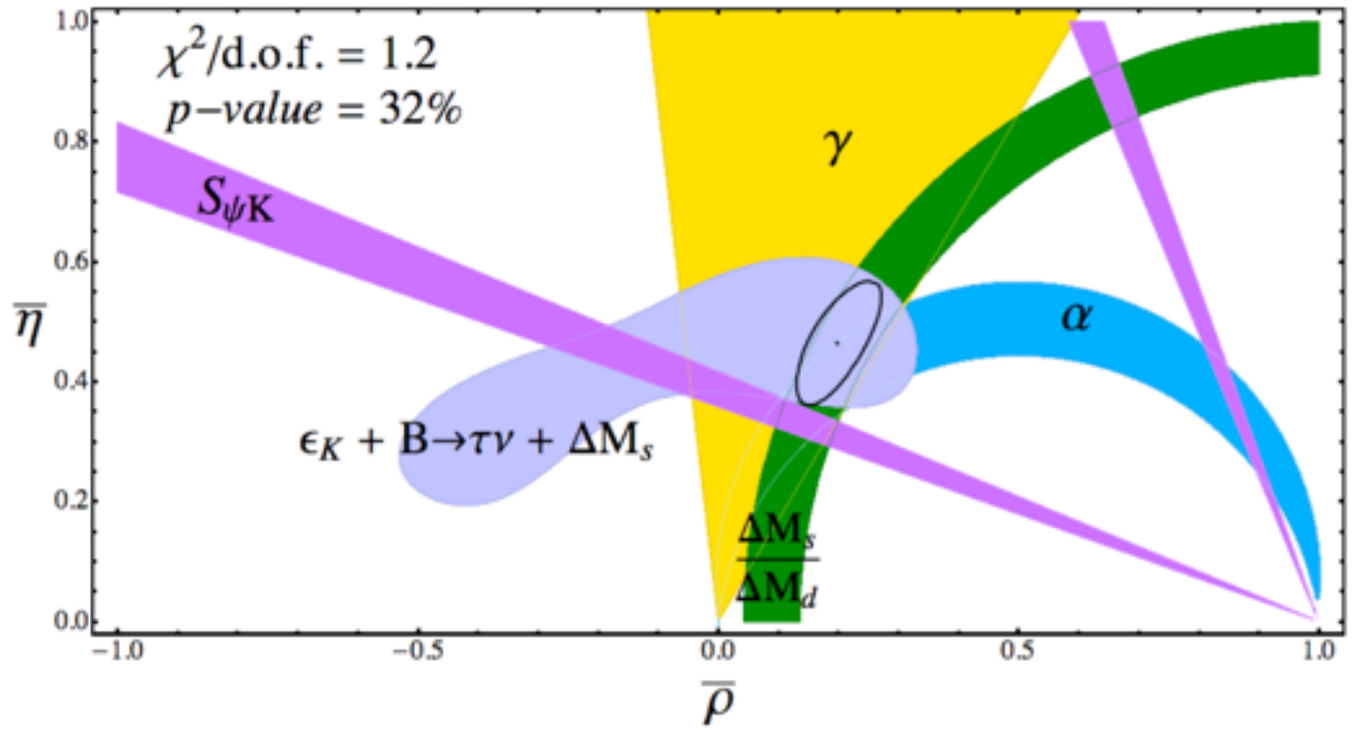
RBC/UKQCD heavy-light physics program

- Until recently, **only two lattice collaborations have been calculating B-meson hadronic weak matrix elements needed for CKM matrix element determinations and unitarity triangle fits using three dynamical quark flavors**
  - Both groups use the same staggered gauge configurations generated by the MILC collaboration, so their results are not wholly independent
- We have therefore **established a new heavy-light meson physics program using domain-wall light quarks**
  - Use relativistic heavy-quark action for the b and c quarks
  - *Will provide an essential crosscheck of phenomenologically-important quantities*

Current projects

- **f_B and f_{Bs}** [with O. Witzel]: needed to search for charged Higgs in B→τν decay
  - Needed to implement alternate method to constrain the CKM unitarity triangle that does not require inputs from semileptonic B-decays

[Lunghi & Soni, Phys.Rev.Lett. 104 (2010) 251802]



- **neutral B-mixing matrix elements** [with O. Witzel]: needed to interpret measurements of the B_d and B_s oscillation frequencies as constraints on the CKM unitarity triangle
- **B→πℓν form factor** [with Tokyo U. visiting student T. Kawanai]: needed to obtain $|V_{ub}|$
  - Currently ~2σ discrepancy between inclusive & exclusive determinations

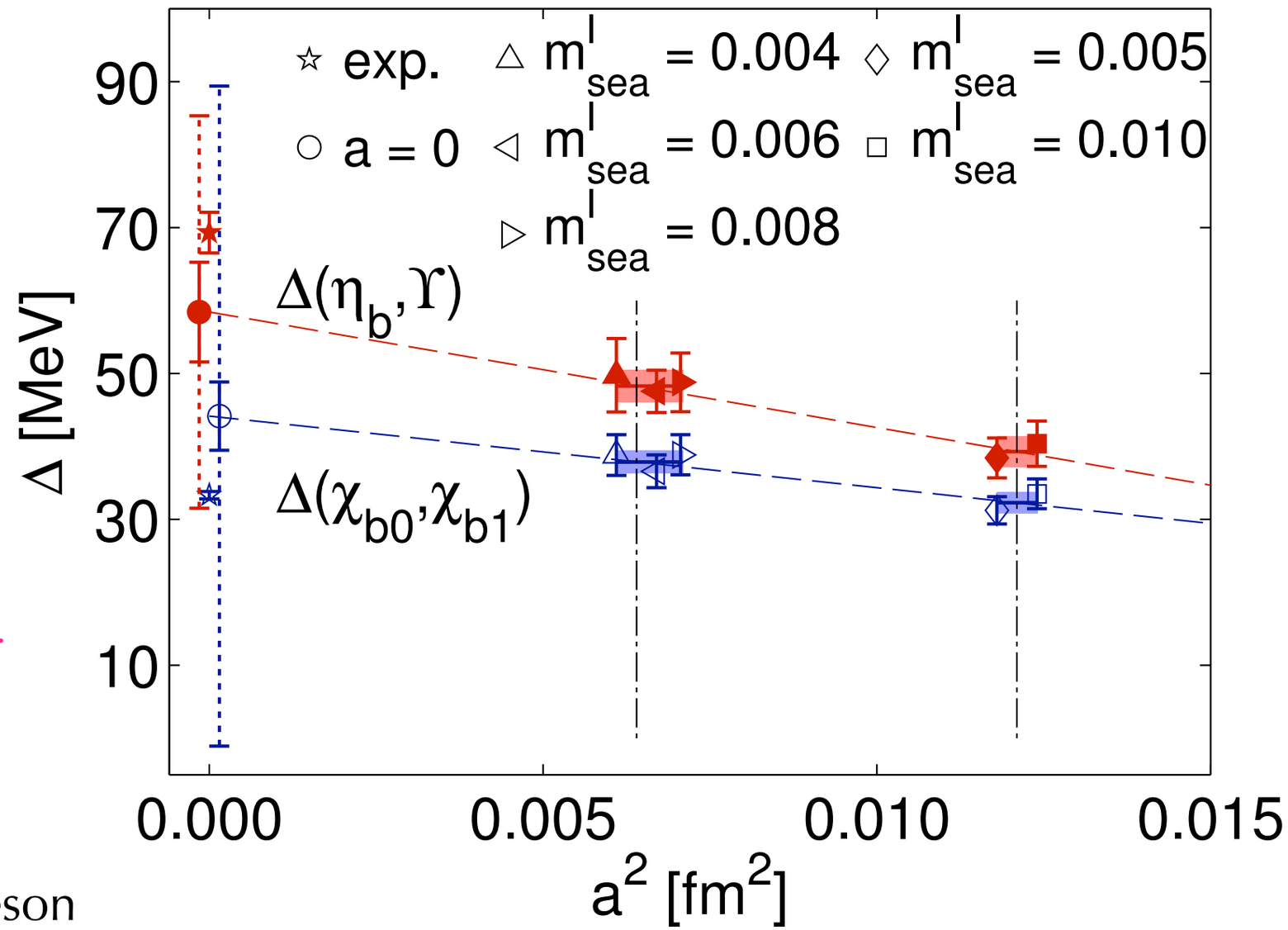
First results

- We tune the parameters of the lattice b-quark action by requiring that we reproduce the correct experimental values of the B_s meson mass and hyperfine splitting (m_{Bs^*}-m_{Bs})

- Can then **make predictions for other states involving b-quarks**

- Find agreement with experiment for the masses of the Υ, η_b, χ_{b1}, and χ_{b2}, as well as their mass-splittings

- Heavy-quark discretization errors large in bottomonium, but expect only few-percent errors in $B_{(s)}$ meson decay constants and mixing parameters due to smaller b-quark momentum in $B_{(s)}$ meson



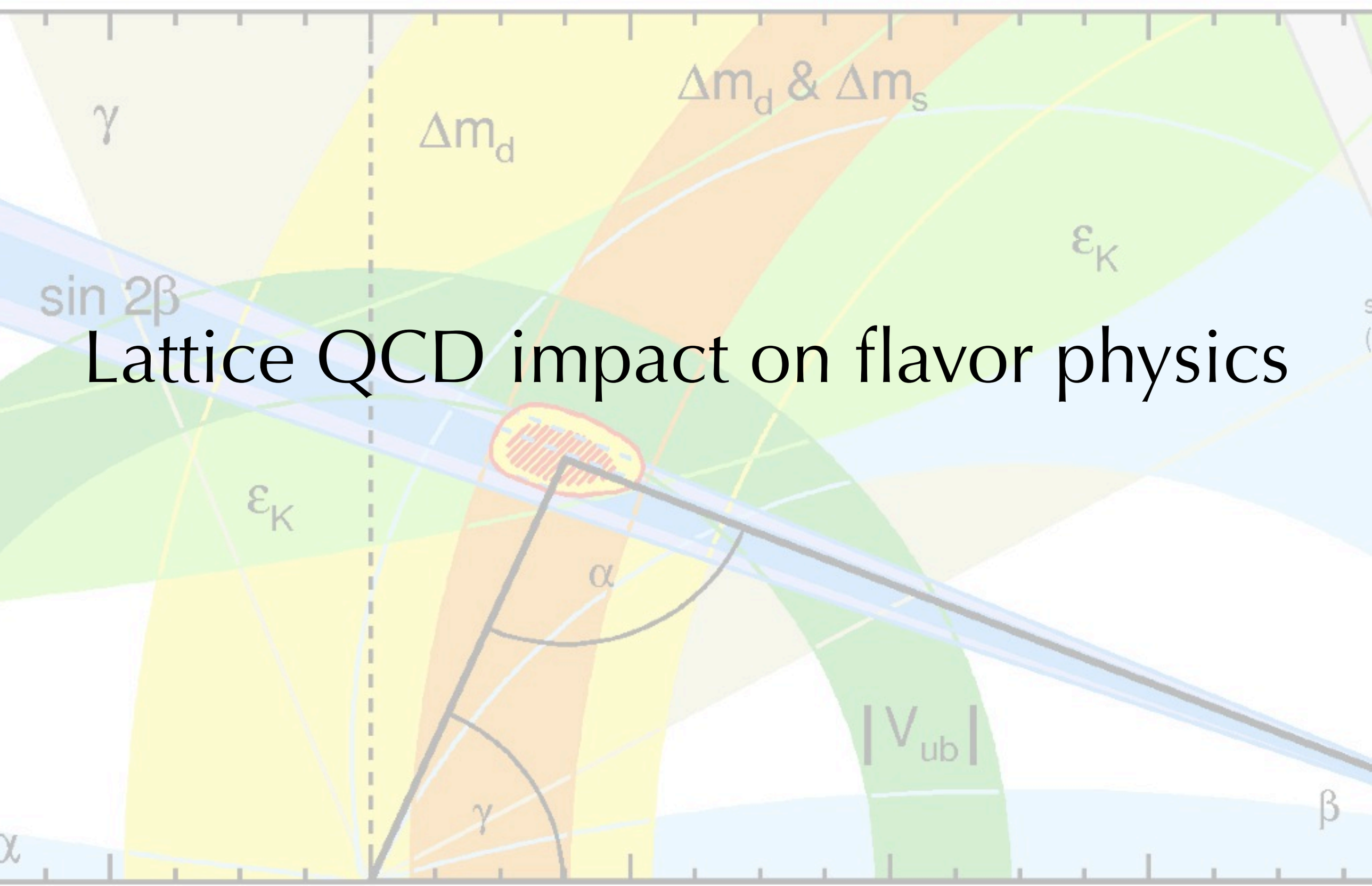
- Provides check of the relativistic heavy quark framework and parameter tuning methodology

Future plans

- **f_D and f_{Ds}** [PhD. thesis project of Columbia U. student H. Peng]: comparison with experiment (assuming CKM unitarity to obtain $|V_{cd}|$ and $|V_{cs}|$) provides a **good test of lattice methods**
  - Because we use the **same relativistic action for c-quarks and b-quarks** agreement with experiment will validate our method and bolster confidence in future calculations of $f_{B(s)}$ and other B-meson matrix elements

- Would also like to extend our program to include:
  - **b,c-quark masses**
  - **$B \to D^* \ell \nu$ form factor**: needed to obtain $|V_{cb}|$
    - $|V_{cb}|$ currently the limiting uncertainty in the unitarity triangle constraint from ε_K
    - $|V_{cb}|$ also the limiting uncertainty in Standard Model calculations of $K \to \pi\nu\nu$-bar branching fractions needed to search for new physics with future experiments at CERN SPS, J-PARC, FERMILAB'S "PROJECT X"

Lattice QCD impact on flavor physics



Lattice averages

[Van de Water with J. Laiho and E. Lunghi]

- Give the current precision of theoretical calculations and experimental flavor-physics measurements, *choice of lattice QCD inputs has a large impact on the global Unitarity Triangle fit*

- At least two realistic lattice QCD calculations that include the effects of the dynamical u, d, and s quarks now available for all standard UT fit inputs

  - ⇒ **Best values for use in CKM unitarity triangle fits and flavor physics phenomenology can be obtained by taking an average**

- Lattice averaging should be done by experts, much like the Heavy Flavor Averaging Group

  - **Only include $N_f = 2+1$ flavor results** in averages that are documented on the arXiv in proceedings or publications with complete systematic error budgets

  - Whenever a source of error is at all correlated between two lattice calculations (*e.g.* use the same gauge configurations, same theoretical tools, or experimental inputs), **we assume that the degree-of-correlation is 100%**

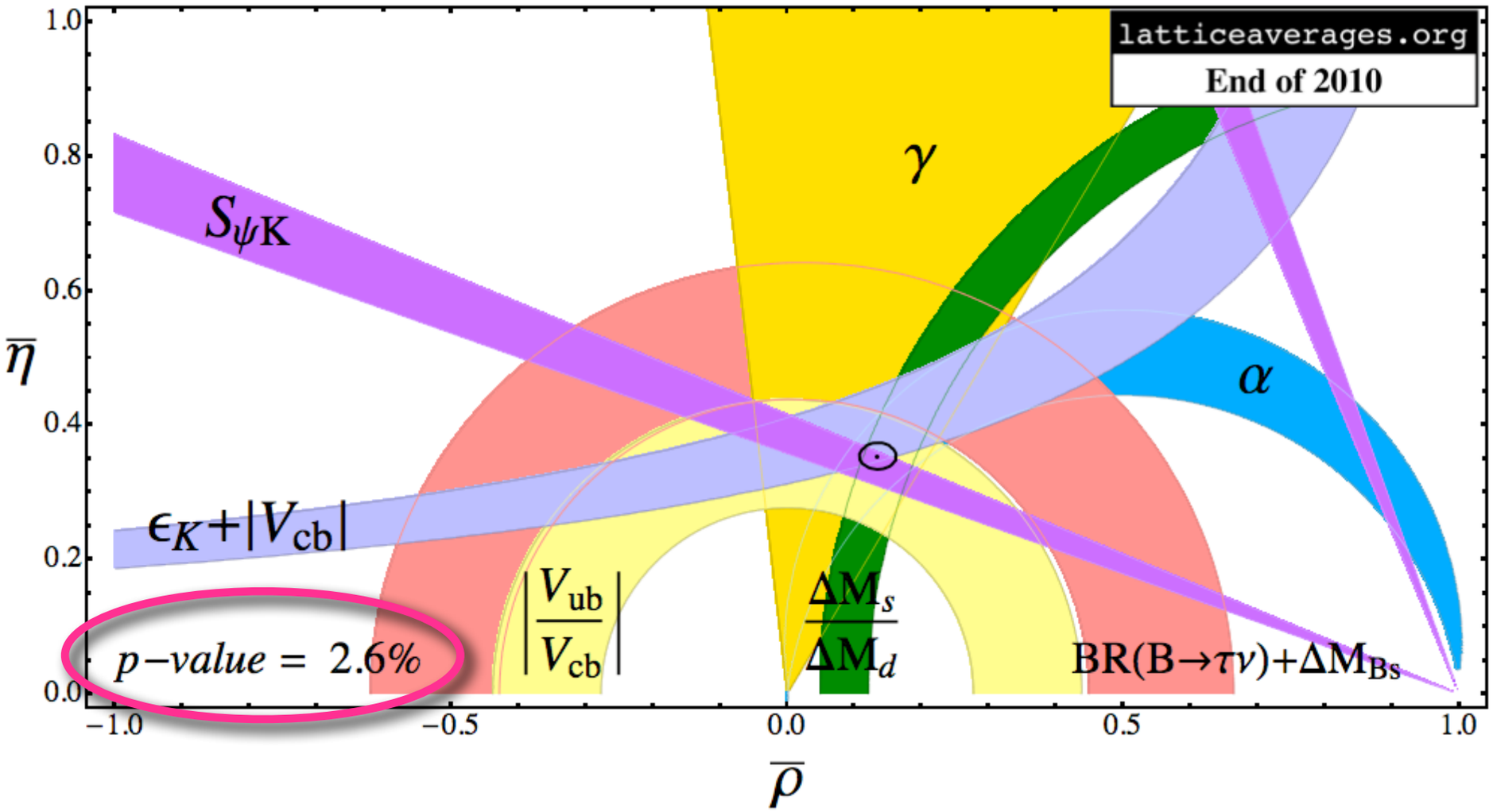
www.latticeaverages.org

- Regularly update averages published in Phys.Rev. D81 (2010) 034503 with new results and make them available on the web

- Results are being used and cited; currently working with editors of B-factories Legacy Book to provide averages to be used by CKMfitter, UTFit, and ScanMeth

Hint of new physics in the flavor sector?

- Improved lattice QCD calculations of kaon and B-meson mixing matrix elements have shrunk substantially the allowed region of parameter space in the ϱ-η plane and revealed a tension in the CKM unitarity triangle
[Lunghi & Soni, Phys.Lett. B666 (2008) 162-165]



- Tension has grown in significance [Laiho, Lunghi, RV, arXiv:1102.3917] and persists even when one omits the more problematic inputs $|V_{ub}|$ and $|V_{cb}|$

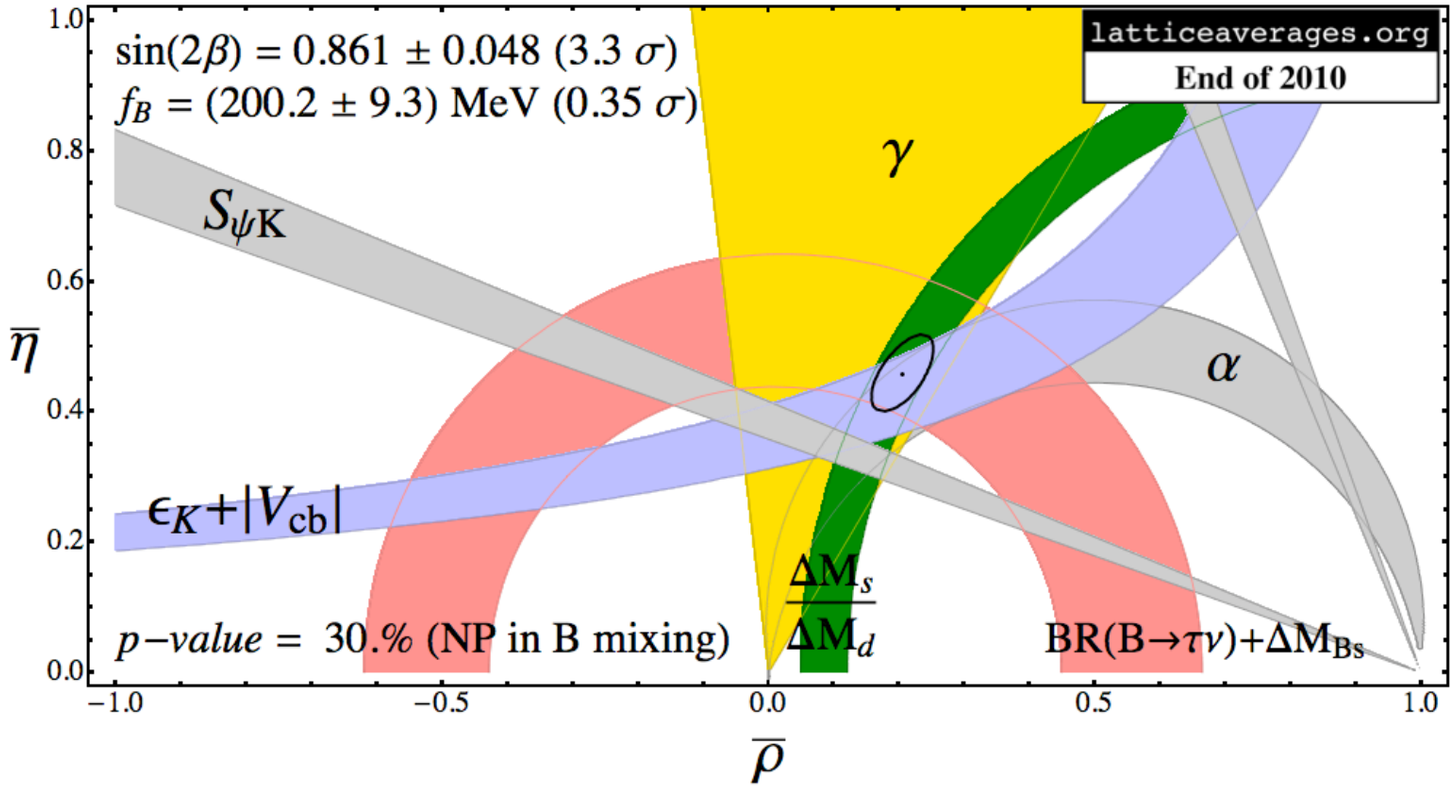
Model-independent interpretation

[Lunghi and Soni, PLB B697 (2011) 323-328]

- Compare likelihood of scenarios of new physics in kaon-mixing, B-mixing, B→τν
  - Omit $|V_{ub}|$ from B-semileptonic decays
  - For B→τν constraint use lattice inputs $\left\{\xi \equiv f_{B_s}\sqrt{B_{B_s}}/f_{B_d}\sqrt{B_{B_d}},\ f_{B_s}\sqrt{B_{B_s}},\ B_{B_d}\right\}$; can then compare predicted f_B with lattice results as check internal consistency of new physics hypothesis

- **Goodness-of-fit best when new physics is in phase of B-mixing**
  (and hence affects $S_{\psi K_S}$)

- Predicted value of f_B agrees well with lattice determinations for this hypothesis



- With greater precision, future lattice calculations of weak matrix elements (when combined with experiment) can be a powerful diagnostic tool to reveal the underlying nature of new physics

Summary and outlook

- Observations are largely consistent with the Standard Model CKM framework, but there are **some indications of a non-Standard Model source of CP violation**
  - Improved precision in lattice QCD calculations of weak matrix elements such as B_K and B-mixing ratio ξ crucial for this observation
- BNL high-energy theory is attacking several of the most important weak-matrix elements for CKM phenomenology
  - Kaon physics program has led to the current best published calculations of the $K\to\pi\ell\nu$ form factor and neutral-kaon mixing parameter B_K
  - Now turning attention to the more challenging target of $K\to\pi\pi$ decay
  - Developing a B- and D-meson physics program using domain-wall light quarks and will post 1st paper this summer
- BNL HET has **expertise in both lattice gauge theory and flavor phenomenology**, and is poised to play a key role in discovering new physics in the flavor sector!